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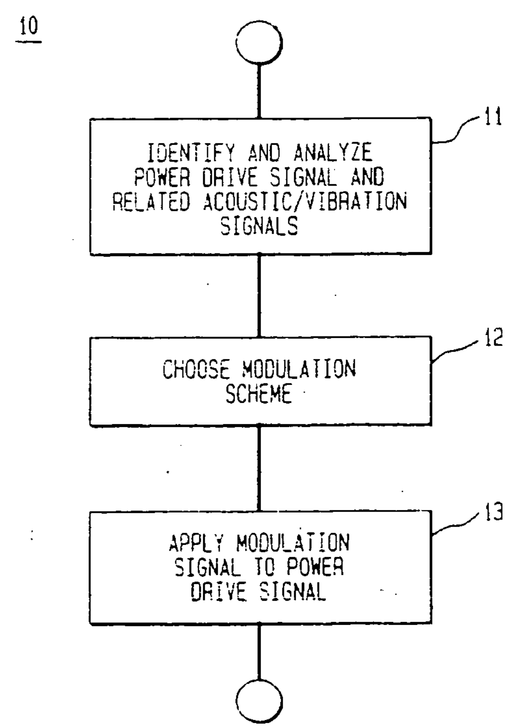
(54) **Method for reducing acoustic and vibration energy radiated from rotating machines**

(57) A method and apparatus for substantially reducing tonal noise and or vibration generated by a rotating machine. The power supplied to the rotating machine or motor drive signal is modulated as a function of time so that the shaft rate of the rotating machine is varied as a function of time. The motor drive signal or power signal can be modulated in an alternating current (AC) machine wherein the shaft rate is related to the power line frequency, as well as a direct current (DC) machine wherein the shaft rate is related to the DC level applied, to alter the shaft rate as a function of time. Such drive power modulation causes the drive signal energy to spread into new frequencies. As a result, the radiated tonal components are spread out such that the strength of the rotating machine's tonal radiation is substantially reduced. In addition, "beating" effects related to the operation of multiple machines can be reduced.

FIG. 1

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## Description

### Field Of The Invention

This invention relates to rotating machinery, and more particularly to rotating machinery that radiate acoustic and vibration energy.

### Background Of The Invention

Rotating machinery will typically introduce both acoustic and vibration energy into any fluids or structures surrounding the machinery. The acoustic and vibration energy can be caused by both random and deterministic processes related to the operation of the machinery. Random processes result in noise or vibration that is spread over a wide band of frequencies. Deterministic processes, on the other hand, often generate energy that is confined to a family of distinct frequencies radiated as "pure" tones. Typically, for a machine having a rotating shaft, the tones are radiated at frequencies that are integer multiples of the frequency at which the shaft rotates. As a result, rotating machines radiate acoustic and vibration spectra that contain both broadband and tonal components.

Those skilled in the art are aware that systems which radiate strong levels of tonal noise are annoying to humans. In fact, noise control engineers are aware that tonal noise can be more annoying to humans than other forms of acoustic noise. As a result, the noise control engineers often focus on the reduction of tonal noise generated by such rotating machinery.

In reducing the tonal noise generated by multiple rotating machines operating in the same environment, of particular concern is the tonal noise generated when two or more machines spin at nearly the same rate. That is, those interested in reducing tonal noise radiated from a plurality of rotating machines within close proximity to each other are particularly concerned with the tonal noise generated when each machine radiates tones at a slightly different frequency than the other machines. In such an environment, the frequencies of the tones radiated from each machine will vary slowly with respect to each other. As a result, the tones will constructively and destructively interact to create tones that "beat". That is, the tones radiated from each machine will interact with each other such that a noise having a given envelope variation ("beating effect") will be perceptible to the human ear. Such a beating effect can be heard in propeller driven aircraft, or in rooms where multiple fans are running. As most are aware, the beating noise can be considered to be particularly annoying to the human ear.

Moreover, since a structure can be characterized by the natural resonant frequencies at which it most easily vibrates, those skilled in the art are also concerned with vibration energy radiated by such rotating machinery. That is, if the vibrational frequency(s) generated by a rotating machine match the natural resonant frequency(s) of a given structure near the machinery, the structure can be forced into strong vibration. The result can be structural fatigue and/or additional acoustic noise generation. As a result, those skilled in the art are continuously concerned with minimizing the effect of such acoustic and vibration energy radiated by rotating machinery.

### Summary Of The Invention

Accordingly, the present invention is directed to a method for substantially reducing tonal noise and or vibration generated by a rotating machine. To attain this, the power supplied to the rotating machine or motor drive signal is modulated as a function of time so that the shaft rate of the rotating machine is varied as a function of time.

In general, one of the operating parameters that defines the shaft rate of a rotating machine is the drive signal imposed upon its motor. In an alternating current (AC) machine, the shaft rate will usually be related to the power-line frequency. In a direct current (DC) machine, the shaft rate will be related to the DC level applied. In either case, the shaft rate can be altered by modulating the motor drive signal as a function of time. This causes the shaft rate to change with time which, in turn, spreads-out the tonal components of the machine-generated acoustic noise and vibration. As a result, the strength of the rotating machine's tonal radiation is reduced.

In one embodiment, the power to a motor that turns the impeller of an air-moving device is varied as a function of time to minimize the impeller-generated acoustic noise heard, and the vibration induced into a structure holding the air-moving device. In another embodiment wherein a multiple number of machines are beating with each other, the tonal noise is reduced by applying a modulating signal to the power of each machine so that the phase relationship between the tonal noise of each machine is randomized, thus reducing the strength of the beating. Thus, the present invention overcomes to a large extent the limitations of the prior art.

Machines to which the invention may be applied include motors of propeller driven aircraft, air-moving devices, compressors, evaporators and centrifuges.

### Brief Description Of The Drawings

FIG. 1 is a flow chart showing the steps of one method for reducing the acoustic and vibration energy of a rotating machine according to the present invention.

### Detailed Description Of Illustrative Embodiments Of The Invention

As stated above, in operation, a rotating machine will impose fluctuating forces on the surrounding fluids

and structures, and the frequencies of those fluctuating forces will be related to the speed of the machine's rotation. For example, in a propeller driven aircraft an occupant will hear noise and feel vibrations at frequencies which are multiples of the engine shaft rate.

In rotating machines driven by electric motors, one of the operating parameters that defines the shaft rate is the drive signal imposed upon the motor. In an AC machine, the shaft rate will usually be related to the power line frequency. In a DC machine, the shaft rate will be related to the DC level applied. In either case, however, the shaft rate can be altered by modulating the motor drive signal as a function of time.

The modulation of the drive power signal causes the drive signal energy to spread into new frequencies, thus causing the motor to change the shaft rate with time. This, in turn, causes the tonal components of the acoustic noise and vibration to spread-out, thus reducing the strength of the tonal radiation at any given frequency.

The amount of spreading (i.e. bandwidth over which the energy will be distributed) depends upon the type and strength of the modulation applied to the drive signal, and on the response of the media surrounding the machine to the new frequency components of the radiated noise. While the response of the surrounding media is difficult to quantify mathematically in a general sense, the effect of the applied modulation on the electrical drive signal can be determined through communication theory.

For example, a drive signal, $d(t)$, applied to an AC rotating machine can be represented as $d(t) = A\sin(2\pi ft + \phi)$. In this representation, the amplitude, A, and the sinusoidal frequency, f, are time-invariant. The shaft rotation rate in revolutions/sec. will be equal to f (Hz). By modulating the drive signal as described in the present invention, a time variation will be introduced into the amplitude, A, frequency, f, and/or phase, $\phi$, of $d(t)$ shown above. Such a modulated drive signal, $d_m(t)$, can be represented in its simplest form as $d_m(t) = b(t)\sin(2\pi f(t)t + \phi(t))$.

In many instances, the most useful forms of $b(t)$, $f(t)$ and $\phi(t)$ are likely to be random functions. For instance, given an AC rotating machine driven by a signal whose nominal phase is $\phi_1$, a relevant form for $\phi(t)$ is $\phi(t) = \phi_1 + \delta(t)$ where $\delta(t)$ is a random variable constrained by some limits (e.g. $-\pi/4 \leq \delta(t) \leq \pi/4$). For a DC rotating machine, an analogous implementation of the method would be to apply random modulation to the input voltage. Assuming the nominal input voltage is B, a relevant form of $b(t)$ is $b(t) = B + \gamma(t)$, where $\gamma(t)$ is a random variable constrained by some limits (e.g. $-B/4 \leq \gamma(t) \leq B/4$). In a refinement of this example, $\gamma(t)$ is a bandpassed pink noise (i.e. constant spectral energy over constant percentage bandwidths).

As is well known from communications theory, the forms of modulation that can be applied to a simple sinusoid such as the drive signal, $d(t)$, include amplitude modulation, frequency modulation and phase modulation. Each of these forms of modulation causes spreading of the signal's energy in the frequency domain. The details of the spreading depend upon the functions chosen for $b(t)$, $f(t)$ and/or $\phi(t)$. That is, without modulation, all the energy in the drive signal will occur at the frequency f. When modulation is applied, the frequency content of the drive signal is dictated by forms of $b(t)$, $f(t)$ and/or $\phi(t)$.

It should be noted that since DC rotating machines are driven using pulsed signals, digital communications theory can be used to derive modulation methods similar the method described above for an AC-powered machine. Thus, whether modulating the power to a DC machine or an AC machine, the modulation causes energy to be taken from the original signal frequency and spreads it into new frequency bands.

Referring now to FIG. 1, there is shown one method of reducing the tonal noise of rotating machines according to the present invention, hereinafter referred to as noise reduction method 10. As shown, the power drive signal and related acoustic/vibration signals are first identified and analyzed, step 11. Then, in step 12, a modulation signal is chosen for modulating the identified power drive signal such that the shaft speed will fluctuate in the desired manner. The modulation signal is then applied to the power drive signal, step 13, to spread the tonal noise over a given spectrum. As a result, the tonal noise radiated from the rotating machine is substantially reduced. Thus, the method according to the present invention overcome, to a large extent, the limitations of the prior art

Systems which utilize rotating machines that require the shaft speed to remain essentially time-invariant, however, can not implement noise reduction method 10, as described above, without causing system performance problems. Some of these time-invariant systems, however, could utilize noise reduction method 10 if noise reduction method 10 included a step for controlling the modulation of the power drive signal so that the mean shaft speed would remain constant over time.

Examples of such time-invariant machines include air moving devices, compressors, evaporators and centrifuges. For these machines, the work done by the machine over a relatively long period of time is the central performance parameter. As a result, fluctuations about the mean for short intervals will not degrade performance. For example, a key design parameter of a small axial cooling fan is the flow-rate through the fan in feet-per-minute (FPM), and the heat load removal rate in watts/min. For such a fan, if the modulation of the power signal is controlled such that the shaft rate fluctuations occur over milli-second intervals and that the FPM over the long-term is maintained, there will be no adverse thermal affects on the system. In addition, the added turbulence due to the shaft rate fluctuation may increase the net heat removal.

There are many embodiments for providing a means for reducing the tonal noise radiated from rotat-

ing machinery by modulating the drive power signal according to the present invention. The above description only includes exemplary embodiments of the many methods for implementing the present.invention. References to specific examples and embodiments in the description should not be construed to limit the present invention in any manner, and is merely provided for the purpose of describing the general principles of the present invention. It will be apparent to one of ordinary skill in the art that the present invention may be practiced through other embodiments.

## Claims

1. A method for reducing the tonal energy radiated from a machine having a rotating shaft, and a motor drive signal for rotating the shaft at a given rate, the method comprising the step of modulating the motor drive signal as a function of time to alter the speed of the rotating shaft as a function of time.

2. The method of claim 1 further comprising the step of controlling said modulating of the motor drive signal to maintaining a mean shaft speed substantially equal to the given shaft rate of rotation over time.

3. The method of claim 1 or claim 2 further comprising the step of identifying and analyzing the drive power and acoustic/vibration signals to determine a modulation scheme for reducing the tonal energy radiated from the machine.

4. A device comprising a rotating shaft which radiates tonal noise, a drive circuit for generating a drive signal to power said rotating shaft, and a modulating circuit for modulating said drive signal to alter the speed of the rotating shaft as a function of time so that the radiated tonal noise is spread over a given frequency band.

5. The device of claim 4 further comprising a control circuit for controlling said modulating circuit to maintain a given mean shaft speed over time.

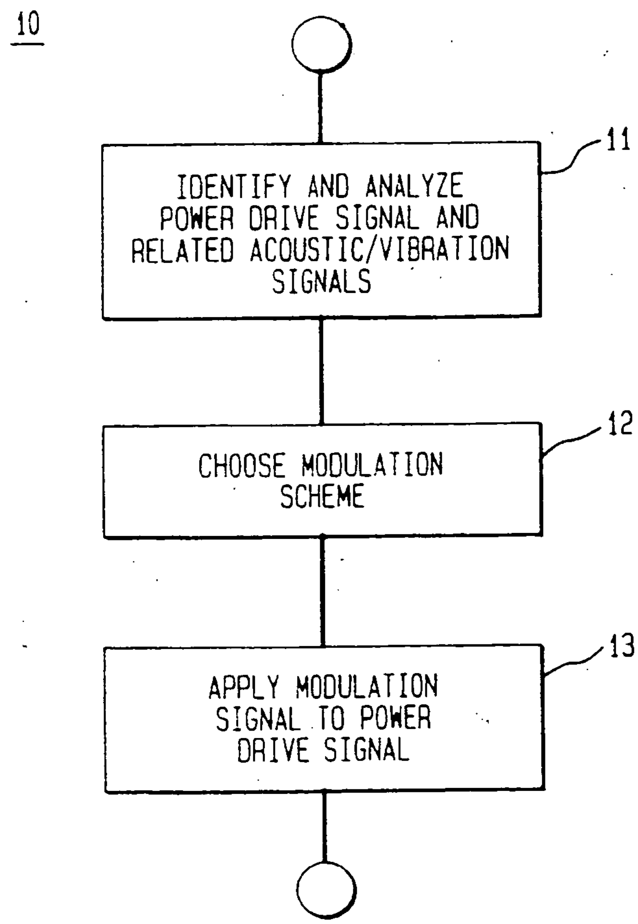
6. The device of claim 4 or claim 5 further comprising a circuit for identifying and analyzing the drive power and acoustic/vibration signals to determine a modulation scheme for reducing the tonal noise radiated from the device.

7. The device of any of claims 4 to 6 wherein said modulating circuit is operable to provide analog feedback and feedforward control for modulating said drive signal.

8. The device of any of claims 4 to 6 wherein said modulating circuit is operable to provide digital feedback and feedforward control for modulating said drive signal.

9. The device of any of claims 4 to 6 wherein said modulating circuit is operable to provide adaptive control for modulating said drive signal.

FIG. 1


10
IDENTIFY AND ANALYZE POWER DRIVE SIGNAL AND RELATED ACOUSTIC/VIBRATION SIGNALS
11
CHOOSE MODULATION SCHEME
12
APPLY MODULATION SIGNAL TO POWER DRIVE SIGNAL
13

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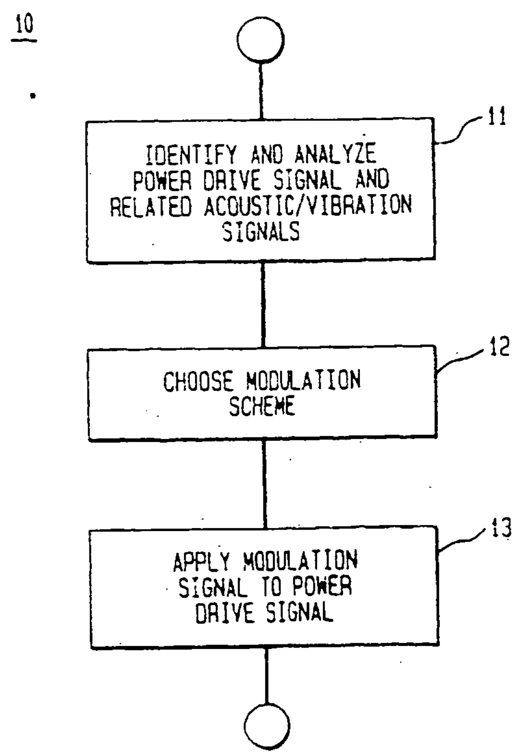


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# EUROPEAN SEARCH REPORT

Application Number
EP 97 30 7433

## DOCUMENTS CONSIDERED TO BE RELEVANT

| Category | Citation of document with indication, where appropriate, of relevant passages | Relevant to claim | CLASSIFICATION OF THE APPLICATION (Int.Cl.6) |
|---|---|---|---|
| X<br>A | DE 41 28 109 A (ZEXEL CORP) 5 March 1992<br>* abstract; figure 4 * | 1,4<br>3,6,8 | H02P7/62<br>H02M7/5395 |
| X | DE 39 30 543 A (BARMAG BARMER MASCHF) 29 March 1990<br>* abstract; figure 1 * | 1,4 | |
| A | GB 2 232 835 A (CHLORIDE GROUP PLC) 19 December 1990<br>* abstract; figure 4 * | 1,4 | |

TECHNICAL FIELDS SEARCHED (Int.Cl.6)
H02P
H02M

The present search report has been drawn up for all claims

| Place of search | Date of completion of the search | Examiner |
|---|---|---|
| THE HAGUE | 10 March 1999 | Beyer, F |

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## ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 97 30 7433

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10-03-1999

| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
|---|---|---|---|
| DE 4128109 A | 05-03-1992 | JP 4112694 A | 14-04-1992 |
| | | US 5130621 A | 14-07-1992 |
| DE 3930543 A | 29-03-1990 | NONE | |
| GB 2232835 A | 19-12-1990 | CA 2051402 A | 08-10-1990 |
| | | EP 0466757 A | 22-01-1992 |
| | | WO 9012446 A | 18-10-1990 |
| | | JP 4504496 T | 06-08-1992 |

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